The image simulator for the Wide-Field Infrared Explorer

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ABSTRACT

The Wide-Field Infrared Explorer (WIRE) is a cryogenically-cooled spaceborne telescope designed to study the evolution of starburst galaxies. Scheduled for a September 1998 launch as NASA's fifth Small Explorer mission, WIRE will employ a 30 cm aperture Ritchey-Chretien telescope to image a 33 by 33 arcminute field simultaneously onto two Si:As BIB detector arrays covering broad bands centered at 12 and 25 microns. A three-part survey strategy calls for moderate-depth (about 15 minutes total integration time), deep (3-6 hours), and ultra-deep (24 hours) fields. For the deep fields, hundreds of background-limited exposures will be recorded by the WIRE instrument over many orbits, and rectified, registered, and combined on the ground. The sensitivity of these final images will be limited by source confusion and is expected to be less than 0.4 mJy (5-sigma) at 25 microns. The WIRE Image Simulator is being developed to simulate the exposures sent down from the spacecraft as closely as possible, including the effects of diffraction, background noise, source confusion, stray light, detector array characteristics, spacecraft jitter and roll, and others. We describe the design and implementation of the simulator, with particular emphasis on the generation of point-spread functions. The simulator is written in C for use on Unix workstations, and we assess its performance. Sample raw and combined images are displayed, and the image processing steps are outlined. The uses of the simulator to verify that mission requirements are met, to optimize observing strategy, and to test data analysis techniques are also described.

1. INTRODUCTION

The Wide-Field Infrared Explorer[1,2,3,4,5] (WIRE) is a cryogenically-cooled infrared spaceborne telescope intended to study the evolution of starburst galaxies and to search for protogalaxies. It will conduct a deep survey of the faint infrared sky by recording repeated images taken at 25 μm and 12 μm. Hundreds of these images will be registered and combined in ground processing. The deepest of the resulting final images will reach the "confusion limit", meaning that the noise in the images will result mainly from multitudes of faint, overlapping galaxies.

The WIRE Science Image Simulator is designed to produce image data that mimics as closely as possible the image data that will be returned by the WIRE instrument. The simulator uses the best available data on instrument parameters and our best estimates of how the faint infrared sky will appear when viewed by WIRE. In its broadest sense, the simulation effort encompasses science modeling of, for example, starburst galaxy evolution, as well as engineering considerations such as detector sensitivities or spacecraft jitter. The simulator is the bridge between the WIRE primary science and the data that WIRE will record, and will be continually updated not only in the time before launch, but during and even after flight operations.

The purposes of the simulator are:

- Producing test data fOr the data reduction pipeline
- Providing a mans to estimate survey sensitivity
- Enabling numerical "experiments" to evaluate the effects of changes in instrument parameters or survey strategy
- Propagating science models of the infrared sky through the detection process, to determine the accuracy to which key science parameters (such as evolution rates) can be measured.

The most significant challenge in simulating WIRE science data lies in properly modeling the confusion noise caused by high number densities of faint overlapping sources, while still efficiently producing the hundreds or thousands of individual frames that WIRE will record.

The simulation effort is crucial to the success of WIRE because the mission will be only four months in duration. There will be little time to puzzle over problems once on-orbit operations begin. This places a premium on understanding the WIRE data as fully as possible before launch.

2. WIRE BACKGROUND

WIRE was selected as the fifth in NASA's series of Small Explorer[6] missions by a competitive selection process in August 1994. The Small Explorer (SMEX) program is managed by Goddard Space Flight Center (GSFC). WIRE was proposed in 1992 by a teaming partnership of the Jet l'repulsion laboratory (JPL), California Institute of Technology, Pasadena, California, and the Space Dynamics Laboratory (SDL), Utah State University, Logan, Utah. WIRE is scheduled for launch in September 1998, and began its development phase in October 1995.

2.1 The WIRE mission

The WIRE mission consists of a 4-month survey in 25 and 12 μm infrared color bands at sensitivity levels bounded by the telescope's 25 μm confusion limit. The confusion limit is set by the density of the many faint, unresolved sources in the field of view and the resolving power of the telescope. The WIRE survey will detect primarily galaxies with unusually high star formation rates, known as "starburst" galaxies, which emit most of their energy in the far-infared. The number of these faint sources at a given flux level depends on their as-yet-unhewn evolutionary rate.

The objective of WIRE is to answer the following three questions:

1. What fraction of the luminosity of the Universe at a redshift of 0.5 and beyond is duc to starburst galaxies?
2. How fast and in what ways arc starburst galaxies evolving?
3. Arc luminous protogalaxies common at redshifts less than 3?

The WIRE survey will cover over 100 deg^2 of sky and detect sources 200-500 times fainter than the IRAS Faint Source Catalog,' at 25 μm and 500-2000 times fainter at 12 pm. The resulting catalog, expected to contain at least 30,000 starburst galaxies, will reveal their evolutionary history out to redshifts of 0.5-1 and the evolutionary history of extremely luminous galaxies beyond redshifts of 5. This will be the first significant galaxy survey to probe these redshifts at far- infared wavelengths where extinction effects arc small and where most of the luminosity of starburst galaxies, and possibly of'the Universe, can be measured.

2.2 The WIRE instrument

The WIRE instrument is a cryogenically-cooled 30 cm Ritchey-Chrétien telescope system that illuminates two 128x128 arsenic- doped silicon infrared detector arrays. A passive, two-stage solid hydrogen cryostat maintains the optics colder than 19 K and the detector arrays below 7.5 K. The filled cryostat will contain about 4.5 kg of solid H_2, which corresponds to about 51 kg of liquid helium. The optical system consists of the telescope primary and secondary mirrors, a dichroic beamsplitter, onc optical passband filter, and baffles. The two channels of the instrument cover broad bands centered near 12 μm and 25 μm; the 25 pm band is the primary onc for detecting starburst galaxies. The telescope focal length is 1.00 m, and the detector array pixels measure 7S μm on each side, yielding a 33x33 arcminute field of view in each passband. The angular size of the pixels projected onto the sky is 15.5 arcseconds. Infrared stimulators will be available to briefly illuminate the detector arrays for calibration purposes. The instrument contains no moving parts.

2.3 Survey and observing strategy

The WIRE survey will consist of three parts. The moderate-depth survey is designed to maximize the detection of distant protogalaxies. 60% of the survey time will be spent on this survey, covering hundreds of squat-c degrees, with about IS minutes total exposure time on each WIRE field. 30% of the survey time will be spent on the deep survey, with a total integration time of several hours pcr field, set by the point at which confusion noise is equal to instrumental noise.. The goal of this survey is to obtain a large sample with the largest lookback time at a given luminosity, which will require covering tens of square degrees to this depth. Finally, the ultra-deep survey will usc about 10% of the survey time early in the mission to observe a fcw WIRE fields for 24 hours or more total exposure time, to measure the confusion limit.

To reach such large cumulative exposure times, WIRE will use a s[arc-and-dither observing technique. During a ten to fifteen minute orbit segment when the target field is near the zenith, the instrument will record a number of short (48 to 64 s) exposures, each separated by a small slew or "dither." This technique will allow estimation of instrumental offsets and diffuse foreground mission so they may be removed from the data. Stimulator flash sequences maybe inserted for calibration. Each target field may be reacquired on subsequent orbits to accumulate sufficient exposure time and to allow detection of moving or variable sources.

3. PROCESS FLOW

Figure 1 is a simplified dataflow diagram giving an overview of the Science image Simulator. The items in closed boxes can be thought ofas verbs, while those in between horizontal lines are nouns. Briefly, the major steps in the simulation process arc:

1. Science models of galaxies and stars arc used to generate sources for a WIRE field
2. The generated source fluxes arc convolved with the point spread function (PSF) and placed into a high-resolution "truthimage". A large number (> 200,000) of galaxies arc placed in order to adequately represent the confusion noise.
3. The truthimage is sampled to create WIRE frames, each of which corresponds to a single WIRE "exposure." Observing parameters (such as dither patterns, number of frames per orbit segment, pointing errors, exposure times, etc.) and instrument parameters (e. g. detector quantum efficiency and read noise, system transmission, optical distortion) arc used to add appropriate noise terms and other defects.

The implementation of the simulator will be discussed in greater depth in the next section.

4. IMPLEMENTATION

The WIRE Science Image Simulator is not a single program, but is a collection of programs and associated data. The code is written in C and C++. The main output is images in FITS format corresponding, to the detector array data WIRE will record. Intermediate files arc stored in ASCII, binary, or 1'1'1'S format, and include source lists, PSF images, truthimages, and other images corresponding to various properties of the WIRE instrument. We have recently begun using a C++ FITSIO library made available by Allen Farris of the Space Telescope Science Institute, and arc converting all binary intermediate files to FITS format for gr-cater portability. The remainder of this section discusses each step of the simulation in detail.

4.1 Source generation

Galaxy fluxes arc generated from an empirical starburst evolution model.[8] The model translates the local luminosity function for starburst galaxies backward in time, optionally applying density or luminosity evolution, The model gives the number density of galaxies as a function of 25 μm flux and redshift. From this 2-dimensional population function, samples arc drawn randomly using a generalization of the 1 -dimensional rejection technique.[9] "1'hen, 12 pm fluxes for each source are computed using a color-luminosity relation[10] derived from the IRAS Bright Galaxy Sample.[11] In this way, over 230,000 galaxy flux pairs arc generated pcr WIRE field to be simulated.

Stars are generated from a model[12] of the Milky Way based on IRAS data. For fields near the North Galactic Pole, typically 500 star flux pairs arc generated per WIRE field.

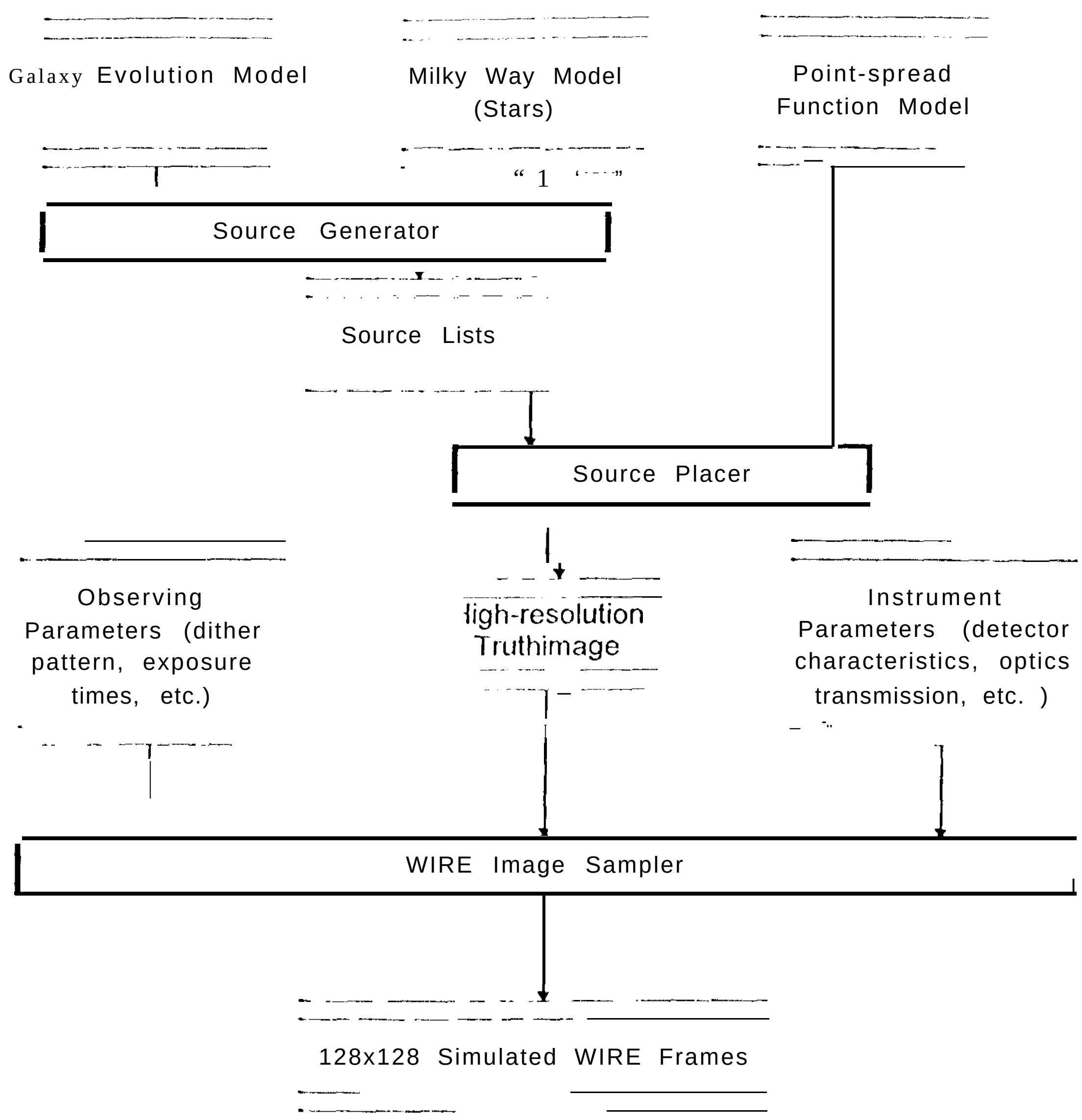

Figure 1:7 'op-Level Simulat ion Dataflow Diagram

4.2 **Point-spread** function generation

Optical diffraction and spacecraft jitter effects arc modeled by a point spread function (PSF). Currently a single on-axis PSF is used for the entire field of view. The procedure for generating the system PSF is described in general terms by the following steps:

1. Calculate diffraction PSF's at a number of intermediate wavelengths (e.g., every 0.5 μm within the passband).

2. Calculate a total diffraction PSF as the weighted sum of these PSFs. Use weights proportional to $\lambda^{1.5}$ in order to model (to first order) the spectral characteristics of the point sources of interest (unresolved galaxies).

3. Calculate a Gaussian jitter PSF of appropriate parameters (e.g., $\sigma_x = \sigma_y = 3$ arcsec). The motion blur due to spacecraft jitter is modeled by this 2-dimensional Gaussian distribution. Based on data characterizing the spacecraft attitude control system, the Gaussian shape has been shown to be appropriate for integration times of 8 s and longer[13].

4. Convolve the total diffraction PSF with the jitter PSF to obtain the system PSF.

In the WIRE simulator, diffraction PSFs (step 1) can be calculated either by computing a standard analytic. formula[14] for the PSF ofa telescope with a central circular obscuration, or by Fourier-transforming a 2-dimensional function representing the telescope aperture using a Fast Fourier Transform (FFT). The FFT has the advantage of allowing simulation of the diffraction caused by the trapezoidal obstructions duc to the struts that support the secondary mirror. Two implementations of the FFT arc available: a mixed-ractix (8-4-2) FFT[15] and a radix-2 pruned FFT[16]. The FFT methods of diffraction PSF computation may be used for aperture shapes for which analytical formulas are unavailable. The struts supporting the secondary mirror are such an obscuration. The PSFs arc created as follows, based on a maximum aperture pixel size, $w_{apix,max}$, chosen to be sufficiently small to represent the size of the aperture features of interest and to avoid "staircase" effects in the drawing of the aperture (actually the exit pupil).

1. Determine N , the length of the FFT required to arrive at the PSF pixel size desired.

   $$N = \frac{f \cdot \lambda_{max}}{w_{pixel} \cdot w_{apix,max}},$$ rounded up to the next higher power of 2, and where

   f = focal length (in meters), and

   w_{pixel} = width ofa (square) pixel (in meters).

2. For each λ chosen across the passband do the following,:

3. Determine the size of aperture pixel, w_{apix}, required to arrive at the desired PSF pixel size: $w_{apix} = \frac{f\lambda}{w_{pixel} N}$

4. Check that the aperture is at least critically sampled. Otherwise the FFT computation will give incorrect results duc to aliasing of frequency components.
5. Determine vertices of the trapezoids representing the strut obstructions.
6. For each aperture row define a set of intervals based on the intersections of the row and the objects (trapezoids and two circles) representing the apcr-lure.
7. Prune the intervals down to a minimal set of intervals describing each row. For proper normalization calculate the numerical aperture, A, as the sum of all the intervals describing the aperture.
8. For each row:
   a) load the real part of elements of an N-element complex-valued buffer with 1 if it is inside the interval. Load it with O if it more than a pixel away from the edge of an interval. Load it with the square-root of the overlapped distance if there is an overlap.
   b) Perform the 1-dimensional FFT ofthc contents of the FFT buffer.
   c) Unload the on-grid portion of the buffer back into the array representing the optical transfer function (OTF). If desired for debugging purposes, keep track of the off-grid energy by maintaining a sum of the magnitude-squared values of the other elements of the buffer.
9. Do the same for the columns of row-transformed pupil function.
10. Normalize the OTF image by dividing by N^2A.
11. Compute the PSF as the magnitude-squared value of each complex OTF value.

The pruned FFT takes advantage of the many zeroes required in this computation if a high-resolution PSF is desired. Using a large N for the transform is a method of fast "sine" interpolation. The pruned FFT routine used for the WIRE simulation is modified from the pruned FFT algorithm described in ref. 16. Rather than output-pruning the so-called negative frequencies, the high frequencies were pruned.

The pruned FFT routines perform a radix-2 FFT, however, and the savings in uncomputed multiplies by zero in some cases do not offset the advantages on some computer architectures of the 8-4-2 FFT routine. The mixed-radix routine allows the number of'(butterfly" stages to be reduced relative to the radix-2 implementation, and cacb butterfly computation is more substantial. This eliminates some overhead duc to loop counters and allows compilers to do a better job of instruction scheduling.

The convolution of the diffraction PSF with the spacecraft pointing jitter is implemented in two ways in the WIRE simulator. Initially a direct implementation of the convolution according to the definition was developed. The computation time required by this step was very dependent on the size of the jitter PSF array. Fast convolution was implemented by performing the convolution in the frequency domain as

$$PSF_{system} = FFT\left[FFT^{-1}\left(PSF_{diffraction}\right) \times FFT^{-1}\left(PSF_{jitter}\right)\right]$$

This method of convolution is much faster for the parameters required for the WIRE simulation (see section 5.?.). In addition, fast convolution is more accurate than direct convolution due to the balanced structure of the FFT-based computations (with direct convolution small numbers are added to relatively large numbers more often).

Development of multiple implementations for both the diffraction PSF generation and convolution has provided opportunities to cross-check the calculations. Insistence upon agreement of the results using the different methods has helped avoid the subtle bugs that can easily creep in to a complex computer program.

4.3 Source placement

Sources are placed into high-resolution "truthimages" using the source lists and the PSF for each passband. First, a random position in the truthimage is generated for each source. Second, the PSF is multiplied by a scale factor corresponding with the flux density of the source. Third, the PSF image is binned to the truthimage pixel scale. The PSF image has 4x4 pixels per truthimage pixel, which allows placement of the center of each source to 1/4 of a truthimage pixel in x and Y. Finally, the scaled and binned PSF is added to the truthimage. Each truthimage has 8x8 pixels per WIRE pixel, so the final accuracy of source placement is 1/32 of a WIRE pixel in x and y.

Sources brighter than a certain flux density cutoff (including all stars and galaxies that will be detectable as discrete sources) are placed into the truthimages using the full 1280x1280 PSF image. To save computation time, all sources fainter than the cutoff are placed into the truthimages using only the central 160x160 portion of the PSF images.

4.4 Observing parameter generation

The observing parameters specify the orientation of the focal plane on the sky for each image, the amplitude of time-varying components of the background (such as stray light) for each image, and the location and brightness of stimulator flashes. A "dither pattern" specifies the commanded small slews between each frame of an orbit segment. Small pointing errors are added to the commanded slews. Boresight angle variations are also modeled by small random changes from frame to frame. The pointing errors may accumulate from frame to frame over each orbit segment, or may be chosen to be independent of each dither. each observing segment. The amplitude of time-varying bakeground components can vary linearly over each observing segment, with a random error added if desired.

4.5 Production of WIRE images

The truthimages and observing parameters are used to generate simulated WIRE images. The truthimage is resampled based on the position errors in the observing parameter file, and the optical distortion. Optical distortion characterizes the change in image height with off-axis angle relative to the paraxial approximation. It is characterized by a file giving the coordinates of detector vertices in object space. The file is currently generated by curve-fitting to data points output by the. optical design program. Optical distortion and changes in boresight or roll angle are included in the mapping to WIRE pixels, as specified in the observing parameter file. The truth images are periodic; that is, sources are placed so that the left edge matches the right edge, and top matches the bottom, so that pointing offsets that cause part of a frame 10 fall off the truth images can be accomodated via periodic sampling.

After resampling the truthimage to the WIRE scale, backgrounds, read noise, dark current, bad pixels, and response variations are added. A stray light pattern is scaled according to the observing parameters and added in as well. The final output of the simulator consists of WIRE frames in FITS format.

5. STATUS AND PERFORMANCE

5.1 Current features

Table I summarizes the major simulation features that have been implemented to date. Most of these features have been described in section 4.

Table 1: Simulator features implemented to date

Description
Original 25 μm simulation, galaxies only
Speed-up of truth image generation
Improved on-axis PSF model (including diffraction from vanes)
Two-color simulation including stars
Stray light pattern and time variability
Fast convolution for jitter convolution
Pruned-FFT code to speed up diffraction calculation
Included distortion and roll into the simulation
Implemented more flexible dither patterns
Pixel-to-pixel response variations
Detector nonlinearity (quadratic)
Dead pixels
Dark current frames
Optics transmission vs. position in focal plane
Stimulators

5.2 Execution time

PSF generation benchmarks were run on an unloaded 70 MHz Sun UltraSPARC with 128 Mb of RAM. The code was compiled with the Apogee C++ compiler, version 3.1, with optimizations selected by -fast. The diffraction calculation was performed at increments of 0.5 μm resulting in twelve diffraction PSF array calculations for each passband. For the 12 μm passband the aperture was described with pixels no larger than 36 dots per-inch (dpi); for the 25 μm band 72 dpi was used. Along with current WIRE specifications this resulted in a transform size of 32,768 in both cases. Although the formula method does not model diffraction from the struts, it was also included for reference. Computing the 12 μm PSF over a 1280x1280 grid took 375 s, 725 s, and 540 s for the formula, mixed-radix FFT, and pruned FFT, respectively. Computing the 25 μm PSF over a 1280x 1280 grid took 375 s, 1632 s, and 1186 s for the formula, mixed-radix FFT, and pruned FFT. In both cases the pruned FFT method is about 25% faster than the mixed-radix FFT method.

When the central 160x 160 portion alone is computed, the formula method scales by a factor of $1280^2/160^2 = 64$ to give a time of 6 s. Neither FFT method scales down by such a large factor since the transform size is fixed, but the pruned FFT speed does improve relative to the mixed-radix FFT. Computing the 12 μm PSF over a 160x 160 grid took 370 s for the mixed-radix method compared to 175 s for the pruned FFT method. For the 25 μm PSF the times were 840 s and 295 s. The pruned FFT method outperforms the mixed-radix method by factors of 2 to 3.

For the current simulation parameters a 59x59 array representing the jitter PSF is required to obtain good accuracy for the final PSF using direct convolution. To convolve this with the 1280x1280 diffraction PSF image requires 5 ıs s for the direct method. The same computation requires 70 s and 90 s using the mixed-radix FFT and pruned FFT code, respectively.

The remainder of the simulation code is less memory- and CPU-intensive, and benchmarks were run on a 90 MHz Pentium personal computer running the Linux operating system and containing 32 Mb of RAM and SCSI-II internal hard drives. Execution times for various portions of the simulation were:

- For source generation of 239,000 flux density pairs: 2 minutes.
- For source placement of all stars and galaxies into both 12 μm and 25 μm truth images: 41 minutes. This time is roughly evenly split between placing ~4,000 bright sources with the full 1280x 1280 PSF, and the remainder with the central 160x160 portion of the PSF.
- For observing parameter generation: a few seconds.
- For WIRE image generation: 2.1 seconds/image when distortion and roll jitter are simulated; otherwise a faster implementation may be used, with a time of 0.35 seconds/image.

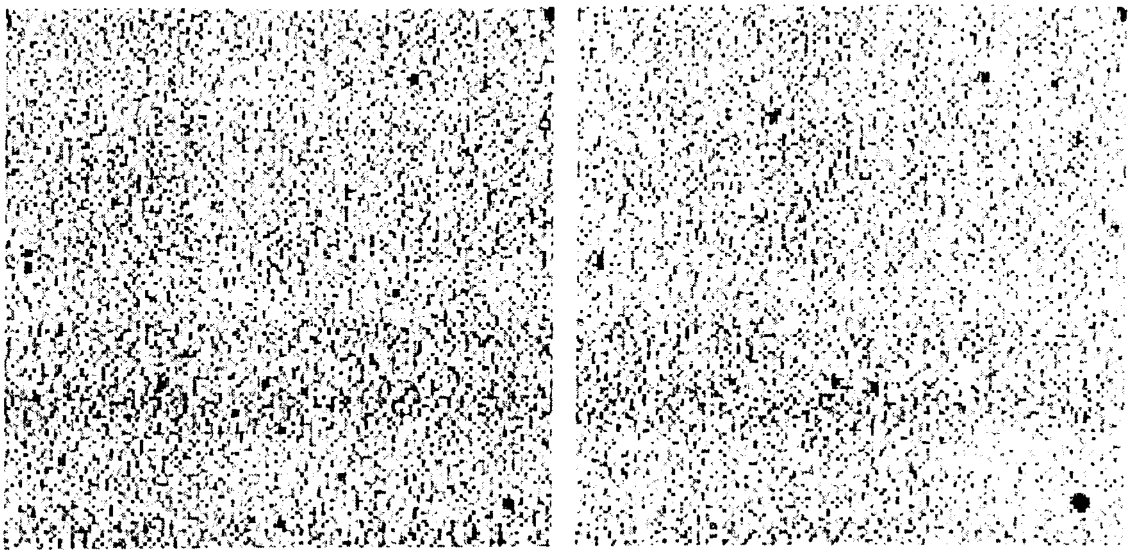

Figure 2 Single 48-second frames for 12 and 25 microns

5.3 Image processing steps

Image processing and data reduction are not a part of the simulation, but we outline the steps here for context. For each observing segment, a background image is formed from the median of the WIRE frames. This background is subtracted from each image in the segment. Next, positional offsets are determined based on common sources in the images. These offsets are used to register the images onto a grid with 2x2 pixels per WIRE pixel, and the images are coadded.

5.4 Sample output

Figure 2 shows sample 12 μm and 25 μm frames as generated by the simulator. These images represent a single 48-second WIRE exposure. The dark spots signify relatively bright (several tens of mJy) sources. Sources that are much brighter in the 12 μm channel are stars, and those that show up more readily in the other channel represent galaxies. The noise is dominated by instrumental noise (mainly shot noise from the infrared background), and is independent from pixel to pixel.

Figure 3 shows coadded data for a deep frame. These images represent a total of 3 hours of cumulative exposure time, and were formed by processing 225 individual simulated WIRE frames according to the procedure described in section 5.3. Hundreds of discrete sources are visible. The faintest 25 μm sources have flux densities of around 0.5 mJy. The lumpy background in the images is the confusion noise caused by multitudes of still fainter, overlapping galaxies. This noise component sets the ultimate limit to WIRE sensitivity, as no increase in integration time can reduce it.

5.5 Further features

A number of features are planned for future incorporation into the WIRE Science Image Simulator:

Infrared Cirrus: The wispy, filamentary emission from Galactic dust clouds will be taken from IRAS data and added to the simulated truth images.

Zodiacal light variation: Emission from the zodiacal dust cloud is the dominant contributor to the background that WIRE will observe. This background will change for a given target field with solar elongation angle.

Radiation hits: Energetic particles may saturate WIRE detector array pixels, and could elevate dark current for a short time.

Temperature changes: Small changes in detector temperature could cause large variations in detector dark current. These variations are currently expected to be small.

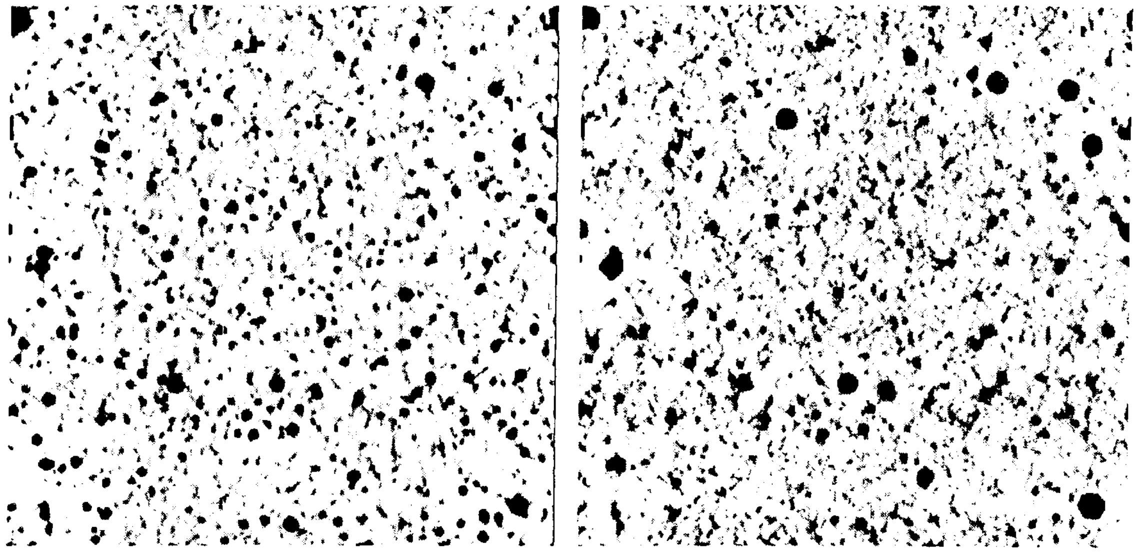

Figure 3: Deep coadded images for 12 and 25 microns

Better treatment of jitter: Presently, the spacecraft pointing jitter is modeled by a 2-dimensional Gaussian distribution that is constant with time. The simulator will be enhanced to use simulated pointing data in order to study its effects on the final PSFs in the processed data.

Aberrations: PSFs that are slightly defocused will be implemented, as will off-axis PSFs with small optical aberrations.

Variable stars and asteroids: Sources that vary with time in brightness or in spatial position will be included

Large-scale structure: Galaxies are not randomly distributed on the sky, but instead tend to cluster along "walls" or "chains Such spatial correlations will be introduced into the placement of galaxies into the truthimages.

6. SIMULATION ANALYSIS

An important application of the simulated WIRE data is to process it through the data reduction pipeline, and compare the photometry of extracted sources with the "true" flux densities of the sources placed in the truthimages. At present the DAOPHOT crowded-field photometry package[17] is used to measure the brightnesses of objects in the images. Then completeness and reliability statistics may be computed from the "truth lists" and the detected list.

The real power of this analysis is apparent when comparing statistics derived from two simulation runs with only one or two small parameters changed, and all else kept constant. This kind of a differential measurement can uncover relatively small effects that can have large impacts on survey sensitivity. At present we are studying the effects of small time variations in a spatially-varying background component due to stray light. We are also analyzing simulated data to determine which "dither patterns" will enable removable of such background components in ground processing.

The statistics of processed simulated data are also useful for uncovering coarser effects. For example, the 12 μm data from the deep survey had been expected to be limited by instrumental noise rather than by confusion noise. The simulated data from our very first two-color simulation run showed that the sensitivity of the deep survey data will be limited by confusion noise in the 12 μm channel as well as the 25 μm passband.

7. CONCLUSION

The WIRE Science Image Simulator produces high-fidelity simulated WIRE images, efficiently and effectively modeling the confusion noise that will limit the deepest portions of the WIRE survey. Enhancements are planned to simulate additional artifacts that are expected to be present in the WIRE data. Analysis of simulated data is being Used to study the impact of a number of parameters on the WIRE data.

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